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HIGH PRECISION POINTING CONTROL FOR WFIRST CGI INSTRUMENT*

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Coronagraph Instrument (CGI) is one of two instruments on the Wide Field Infrared Survey Telescope (WFIRST), a NASA observatory, currently planned to launch in 2025. CGI is a JPL instrument and includes an imaging mode and a spectroscopic mode to perform exoplanet direct imaging and spectroscopic characterization of planets and debris disks around nearby stars. In order to achieve a very tight contrast stability, it requires pointing stability of 0.7 milliarcsecond (mas) RMS over the duration of the observation. This paper discusses CGI pointing architecture and approach to achieve this level of pointing performance, and flight implementation of the pointing system. The architecture is based on nested loops to reject Line Of Sight (LOS) jitter due to one of the largest disturbances on board, the reaction wheel assembly (RWA), as well as other disturbance sources, and thermal drift. The control architecture includes spacecraft ACS, as a feedback control that uses the low-order wavefront sensing (LOWFS) camera and Fast Steering Mirror (FSM) to suppress the telescope pointing drift and jitter, and a feedforward control, that is used to reject sinusoidal tones of the RWA. The LOWFS camera uses high flux from the obscured science target to achieve high sampling rate measurements of the LOS. The FSM has a local control loop that is used to linearize the piezoelectric actuators (PZT) hysteresis. Local feedback of the PZT displacement is provided by strain gauge sensors. This paper will present various aspects of the controller design, some sensor modeling, performance simulation, and operational constraints during CGI observations to meet tight pointing requirements. Some results from our Control Analysis Simulation Testbed (CAST) will be reported.

INTRODUCTION

The Wide Field InfraRed Survey Telescope (WFIRST), is a NASA observatory and is planned to launch in the mid 2020s. WFIRST is the top-ranked large space mission in the New Worlds, New Horizon Decadal Survey of Astronomy and Astrophysics.

WFIRST will carry two instruments on board: Wide Field Instrument (WFI) developed at Goddard Spacecraft Flight Center (GSFC), and Coronagraph Instrument (CGI) developed at the

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Jet Propulsion Laboratory (JPL). WFI is designed to perform Wide Field imaging and surveys of the near infrared (NIR) sky. CGI is designed to perform exoplanet direct imaging and spectroscopic characterization of planets and debris disks around nearby stars. CGI's adaptive optics and low-order wavefront sensor will allow the direct imaging of many known exoplanets and performing an essential technology demonstration for future missions. Currently CGI is a class C technology demonstration.

The WFIRST telescope[†] uses existing hardware donated to NASA and consists of a 2.4 meters primary mirror, a secondary mirror, stable structures, actuators, some mounting hardware, and an outer barrel assembly for thermal and stray light control. The telescope was built by Harris Corporations in Rochester NY, and has been structurally qualified and partially assembled. Its mirrors will be lightly refigured to enable the wide field of view of the Wide-Field Imager (WFI), the cornerstone dark energy instrument for WFIRST.

Earth-like exoplanets are between 10 million and 10 billion times fainter than the stars they orbit, depending on whether they are observed at mid-infrared or visible wavelengths. One of the most important technological challenges of this mission is the demonstration that a space observatory can reject scattered starlight to separate the light of the planet from its parent star.

WFIRST CGI, currently being developed at JPL, would be the first high-contrast coronagraph with wavefront control to fly in space, and is set to achieve unprecedent contrast sensitivity for a space-based Coronagraph. CGI has wavefront sensing and control with 10^{-8} contrast sensitivity. WFIRST CGI will also have the first ultra-low noise visible detector and deformable mirrors to reach low-Earth orbit and beyond. When launched, WFIRST CGI will be the state of the art. CGI had a major cost, and technology readiness review in Summer 2017, and is now classified as a technology demonstration. The project passed its SRR (System Requirement Review) in Spring 2018, and is now officially in phase B, since June 2018. The PDR (Preliminary Design Review) is scheduled for Summer 2019.

In this paper, we will provide a status of CGI pointing control development, and current plans to mitigate pointing jitter. We will first give an overview of the WFIRST mission and we will then explain tight pointing requirements to achieve this contrast sensitivity, as well as mitigation strategies to suppress high frequency jitter. We then explain the pointing architecture to achieve this. We will briefly explain different modes of operation, and the Fast Steering Mirror that is being developed at JPL to correct for the high frequency tip/tilt jitter. Finally, we will show some of the latest results from the Control Analysis Simulation Testbed (CAST).

WFIRST MISSION AND CGI

The key components of the WFIRST payload are illustrated in Figure 1. The WFIRST telescope uses existing hardware donated to NASA and is shown in dark red. The Wide Field and Coronagraph instruments are shown with the Instrument Carrier structure that holds them. The L2 halo orbit chosen for WFIRST provides a different thermal environment than that for which the telescope was designed. This will require a modified thermal design, with greater heater power.

[†] WFIRST Project Page: https://wfirst.gsfc.nasa.gov/

The Wide-Field Imager (WFI) is the flagship instrument of the WFIRST mission. The Coronagraph Instrument (CGI) is currently categorized as a class C, Technology Demonstration. CGI is fed from a separate portion of the telescope field of view, with pickoff mirrors across the telescope from the WFI. A tertiary and collimator follow, which convert the aberrated intermediate Cassegrain focus to a collimated beam with a flat wavefront and low field-dependent aberrations. This Tertiary Collimator Assembly (TCA) is located on the stable optical structures of the Optical Telescope Assembly (OTA), to move the toughest optical perturbation sensitivities onto the most stable structures. Coronagraph accommodation is limited to low-cost modifications. The observatory design is driven by the needs of the WFI, and CGI requirements generally must adhere to the thermal, structural, and pointing performance provided by that design. There is considerable interest in conducting parallel observations with the WFI instrument while the CGI has the lead. To enable that, during payload integration and testing, the fixed alignments of the WFI and CGI instruments will be adjusted so that they are optimized at the same telescope alignment.

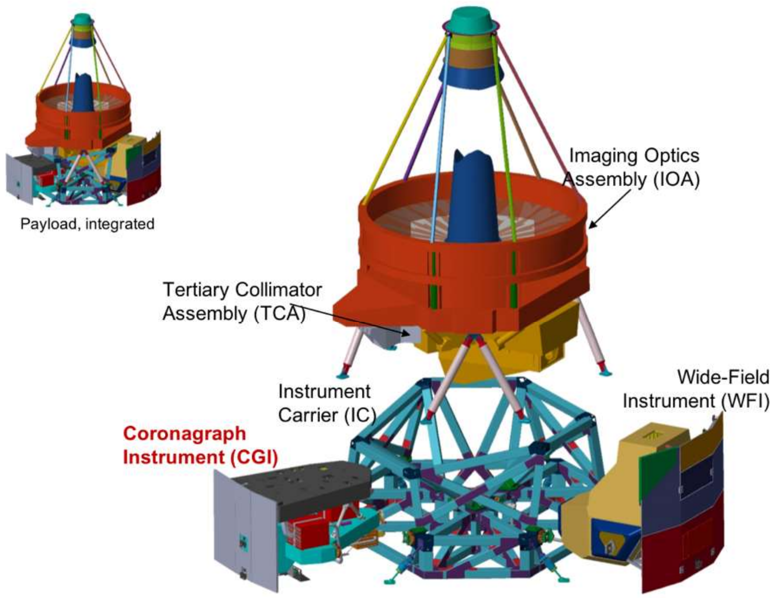

Figure 1: WFIRST payload

Figure 2 shows the block diagram for the WFIRST coronagraph.[1] The CGI Coronagraph Occulting Mask has two operating modes. The layout provides the ability to switch between two coronagraph modes: Hybrid Lyot Coronagraph (HLC) and Shaped Pupil Coronagraph (SPC), simply by selecting different filter wheels masks.

Also shown in the figure are the Low Order Wavefront Sensing and Control (LOWFS/C) and High Order Wavefront Sensing and Control (HOWFS/C) loops.[2] Starlight from the telescope enters the CGI bench through the Fast Steering Mirror (FSM), which compensates for errors in the telescope pointing, yielding sub milliarcsecond pointing stability at the first coronagraph field occulter, where most of the starlight is blocked. This pointing residual error is a key driver of coronagraph performance. The LOWFS/C measures and corrects tip-tilt, focus, astigmatism, coma, trefoil, and spherical aberrations. The slow focus drift is controlled by a focus correction mechanism (FocM), and the remaining aberrations sensed by the LOWFS camera are corrected with the deformable mirrors. Two Deformable Mirrors (DM1 and DM2) correct the wavefront phase and amplitude for high contrast imaging. A selectable mirror sends coronagraph light to either the imaging camera (Direct Imager, or DI) or the Integral Field Spectrograph (IFS). In this way, both the quasi-static and dynamic imperfections of the telescope are suppressed to levels needed to achieve low raw contrast and low variation of contrast, respectively.[3]

Currently, HLC will be used only in imaging mode for shorter wavelengths.[4] The main starlight suppression component in a Hybrid Lyot Coronagraph is a focal plane occulting mask with optimized layers of metal and dielectric. The metal in the mask reflects the majority of the incoming on-axis starlight, and diffracts the transmitted starlight so that it is blocked by the Lyot stop in a downstream pupil plane, while the slightly off-axis planet light is transmitted to the imaging detector or the integral field spectrograph.[5]

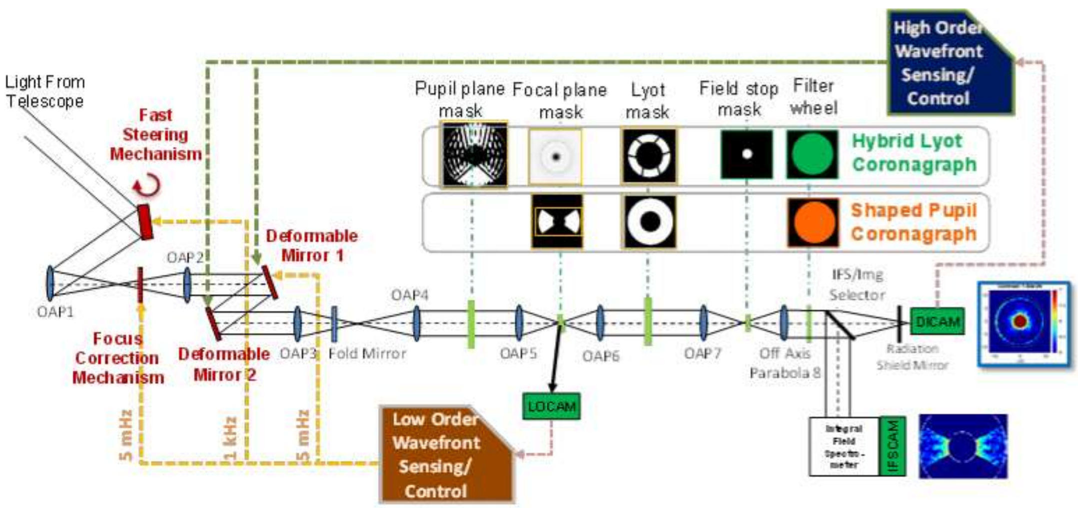

Figure 2. optical block diagram of the WFIRST Coronagraph[6]

POINTING STABILITY REQUIREMENTS AND ASSESSMENTS

The key pointing stability requirement for the WFIRST observatory states that the Line Of Sight (LOS) jitter must be less than 12 milliarcseconds (mas), 1-sigma, in the WFI channel. This includes high frequency LOS jitter that cannot be compensated by the spacecraft Attitude Control System (ACS). WFIRST ACS LOS pointing stability requirement is 8 mas, 1-sigma, and includes the low frequency control errors due to actuator (reaction wheel), sensor noise (fine guidance sensor/WFI), and control algorithm errors over CGI exposure time that is many hours. The reaction wheel errors include friction, ripple torque, and cogging torque.

At CGI level, in order to observe planets, billions of times fainter than the stars they orbit, a tight contrast sensitivity of 10^{-8} or better is required. Average LOS error maps into the average speckle level or contrast stability, which are suppressed starlight residuals after subtracting reference observation from target observation. To meet the CGI contrast sensitivity requirement, the CGI LOS pointing stability must be better than 0.8 milli-arcseconds on the sky between target and reference star observations at the coronagraph focal plane mask.

The CGI PACE (Pointing Acquisition and Control Element) team is responsible for meeting CGI pointing requirements, and devising mitigation strategies to meet extremely tight jitter requirements. Over the past few years, and during Phase A, PACE, GSFC Integrated Modeling (IM), and GSFC ACS teams have been working closely to develop the most feasible approach to meet such tight CGI pointing stability requirements. The IM team at GSFC owns an integrated model of the spacecraft and the observatory, which also includes CGI models. These models are delivered to JPL PACE team to assess CGI pointing performance. The dominant jitter source is due to high frequency structural jitter generated by the reaction wheels. During Phase A, an "exported jitter requirement" was agreed upon by the GSFC IM, and CGI teams. The LOS jitter after the closed loop rejection filter is required to be less than 0.57 mas, 1-sigma. This requirement will be met by operational constraints, and limiting reaction wheel speeds during the CGI observations.

In Phase A, CGI PACE proposed to develop an accelerometers-based sensor suite to measure the high frequency jitter on the observatory, and on the CGI bench. These measurements would then be fed-forward to the control system. However, because of budget constraints, and limitations on placement of accelerometers on the observatory mirrors, this approach is no longer pursued.

During Phase A, CGI bench did not have high fidelity structural models, so it was assumed to be a rigid bench by requiring its first mode to be greater than 200 Hz. Similarly, it was required that the CGI mechanisms mounts, to have a first mode at high frequency, thereby not contributing to pointing jitter. Also, to simplify the modeling approach, the CGI control systems were modeled as simple high-pass rejection filters, and were delivered to the GSFC IM team to determine the operational constraints on wheel speeds during the CGI observations, that would allow satisfying the jitter requirements.

Also, in phase A, it was shown that the FSM/LOWFS tip-tilt control reduces line of sight jitter from 12 mas required by WFI channel, to less than 0.8 mas differential jitter between target and reference star observations at the coronagraph focal plane mask, when limiting the wheel speed between +/- 5 Revolution Per Second (RPS).

CGI PACE owns a pointing budget that includes various error sources. These error sources have different frequency content, and include ACS residuals, sensor, and actuator LOS jitter, FSM induced jitter, CGI bench mechanisms self-induced jitter, as well as high frequency reaction wheels induced jitter. The CGI PACE team has developed a high-fidelity real-time control Analysis Simulation Testbed (CAST) that has modeled various of these disturbance sources, as well as the ACS controller from GSFC, and the CGI pointing control algorithms. CAST runs are used to assess pointing performance in the presence of disturbance sources, while operating the reaction wheels at speeds that were agreed upon with GSFC IM and ACS teams.

The CGI pointing requirements are divided into an acquisition portion and a science observation portion. The acquisition related requirements cover the requirements on ACS that is needed to put a target star in the CGI science camera (Direct Imager) field-of-view (FOV), which is 9x9 arc-seconds. The CGI acquisition requirement of less than 4 arcseconds is needed to ensure the target star is placed within the CGI FOV. During CGI science observations, the ACS is required to bring a target star within 30 milli-arcseconds (mas) of CGI LOWFS capture range.

During Phase B, the PACE team has been working with CGI Mechanical subsystems and other subsystems to relax stability requirements on the CGI bench, and on the mechanisms mounted on the CGI bench. There is an effort under way to assess pointing performance under more realistic assumptions, where CGI bench is not rigid, and has modes at lower frequencies.

The current Phase B CGI bench design has higher fidelity, and the first frequency mode is now at 120 Hz, instead of 200 Hz, and the key mechanisms mounts have their first frequency modes at 150 Hz, instead of 300 Hz. The PACE team has evaluated the newly designed CGI bench model which is more flexible than Phase A assumptions warranted, and has the capability to assess pointing performance under FSM induced disturbances. The overall pointing assessments with the flexible bench integrated into observatory models will be performed in the course of the next few months, towards the Summer of 2019. The GSFC integrated models will be delivered for evaluation to JPL PACE team at that time, and all disturbance sources will be included in the analysis. These results will be demonstrated at the CGI PDR.

The PACE team has completed Level 5 pointing requirements, and has levied down requirements on GSFC ACS, and IM teams, as well as, various CGI subsystems, such as FSM, LOCAM, Mechanical, Electronics, Mechanisms, and PACE.

POINTING STABILITY MITIGATIONS

The dominant jitter source is due to high frequency structural jitter generated by the reaction wheels. The primary mitigation strategy for wheel-induced jitter is passive isolation. Model-based analysis shows the two-stage isolation system meets requirements for an acceptable wheel speed range during CGI science observations.

The Payload Vibration Isolation System (PVIS) between the spacecraft bus (reaction wheel, high gain antenna actuator) and Payload (telescope/instruments) with D-struts would achieve the best isolation performance possible. The second isolation system is the Reaction Wheel Assembly (RWA) isolation system.[7] In order to maintain stable performance, WFIRST plans to avoid moving any mechanisms (e.g. spacecraft high gain antenna actuators or filter wheels) during CGI science exposures.

The Coronagraph Instrument has internal control systems that can correct LOS jitter, outside of the observatory stability mitigation capabilities. CGI pointing architecture includes three nested loops. As mentioned earlier, to simplify the modeling approach during phase A, the CGI control systems were modeled as simple high-pass rejection filters. Both CGI requirements and performance predictions include these closed-loop rejection filters where appropriate. Some operational concepts have been considered to limit disturbances during CGI science observations, such as limiting wheel speeds between +/- 5-10 RPS, avoiding stepping the High Gain Antenna (HGA), and no thruster firing, during CGI science observations. WFIRST has a fixed solar array/sun shield, so solar panel tracking is not a concern. At SRR, models showed that CGI can meet its pointing stability with the aforementioned mitigation strategies.

As part of the GSFC IM process, all prediction results include appropriate model uncertainty factors (MUFs). The MUFs are determined from heritage data and relevant past experience. More extensive analyses will be performed during Phase B of the mission to ensure that the chosen MUFs are sufficient for WFIRST CGI. With the MUFs included, the current best estimates demonstrate that all key stability requirements can be met with reasonable margin. To meet the CGI LOS and Wave Front Error (WFE) jitter requirements, the observatory wheel speed range is currently planned to be limited to +/- 10 RPS, from the nominal +/- 40 RPS. Running the reaction wheels at these lower speeds during CGI observations requires off-loading momentum more often. These operational constraints have been discussed with GSFC ACS team, and wheel speed profiles in these ranges were provided to CGI PACE team for pointing performance evaluation. Currently, the plan is 18 hours between each momentum off-loading at +/- 5 RPS, and 36 hours between each momentum off-loading at +/- 10 RPS. These wheel speed ranges are predicted to allow CGI to achieve its technology demonstration goals.

POINTING ARCHITECTURE

The dominant jitter source is due to high frequency structural jitter generated by the reaction wheels. The pointing architecture to meet tight pointing requirements in presence of high frequency jitter, among other disturbances, requires various loops and sensors with high frequency sampling rates to reject jitter at various frequencies. As shown in Figure 3, there are nested control loops. These control loops together with operational constraints on reaction wheels are critical in meeting CGI tight pointing requirements.

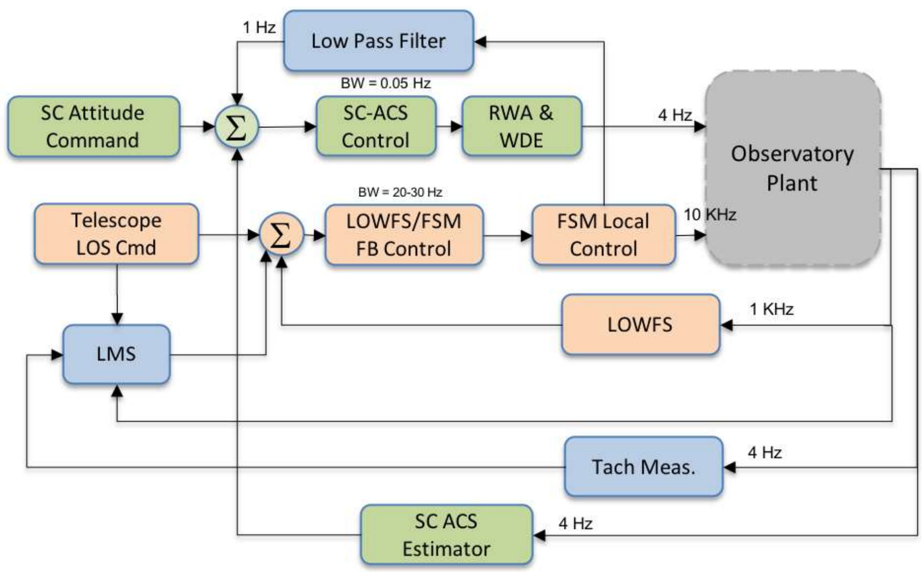

Figure 3. Pointing Control Architecture

The FSM /LOWFS feedback loop uses FSM, for tip/tilt jitter rejection. The rejected starlight from the focal plane mask, is captured by the LOWFS lenses and sent to LOCAM (LOWFS Camera). Line of Sight feedback control uses LOCAM, for tip and tilt measurements. LOCAM measures changes in tip and tilt at 1000 Hz sampling rate, with micro arc-second noise level over a limited band. The feedback control system requires high enough bandwidth to reject high frequency jitter, but this bandwidth must be low enough to avoid unnecessary jitter from the sensor noise. The feedback loop with bandwidth of 20-30 Hz is designed to reject ACS residuals, RWA jitter under 10 Hz, FSM electronics jitter, and FSM-induced jitter, among other disturbances. The current feedback loop will cancel the ACS LOS drift, since the bandwidth of the FSM/LOWFS loop will be much higher than the corner frequency of the ACS control system at 0.05 Hz. The feedback loop will also have some effect on the RWA disturbance since the wheel speeds are in the +/- 0-10 RPS range. Both the fundamental and subharmonics of the wheel imbalances are within the bandwidth of the feedback loop.

The FSM has its local control loop to precisely control the displacement of three piezoelectric actuators (PZTs), using feedback from strain gauge sensors that are on the PZTs. This loop has a bandwidth of 150-200 Hz, and linearizes the PZTs hysteresis, and cancels drift due to creep. This bandwidth is limited by the first structural mode of the mechanism at 900Hz. The FSM control has a prefilter for smoothing DAC noise and a voltage attenuation gain to reduce the input voltage range. Both the prefilter and gain attenuation are used to minimize jitter from DAC noise and quantization error. In order to ensure that the local loop is stable, there are requirements on the first mode of the FSM and its mount. In addition, since the FSM is mounted directly to the CGI optical bench without mechanical isolation, requirements were levied on FSM reaction mass imbalance parameters, and FSM exported force and torque.

WFIRST spacecraft Attitude Control system (ACS) is being developed at GSFC, and in its current architecture has six HR18-250 reaction wheels, eight 22N class thrusters for orbit insertion, and midcourse maneuvers, and sixteen 5N class thrusters for station keeping and momentum unloading. The sensors on-board are Coarse Sun Sensors, IRU, Star Sensors, and a Fine Guidance Sensor (FGS). During CGI observations, for both CGI acquisition and science tracking, ACS control is RWA-based. A low bandwidth ACS feedback loop at 0.05 Hz is used to reject slow ACS drift caused by Solar Radiation Pressure (SRP) torque, as well as other low frequency drifts.

The thermal drift between the CGI, and the WFI fields of view, is planned to be tracked by the ACS. This offset will be offloaded by the CGI FSM strain gauge measurements to ACS, after Low Pass Filtering (LPF). The FSM offset can be thought of as a command offset, but it can also be viewed as a sensor measurement. This measurement will be blended in with the WFI Fine Guidance Sensor (FGS) measurements. FGS measurements blended with smoothed FSM strain gauge measurements produce a correction, avoiding the transients, and attenuating noise at frequencies up to the ACS controller bandwidth.

There is also a feedforward loop to suppress the high frequency tones excited by the reaction wheels. ACS sends tachometer wheel speed measurements, and reaction wheels torque commands to CGI feedforward loop that employs a Least Mean Square (LMS) algorithm[8]. LMS is an adaptive filter that uses reaction wheel speed signals from the spacecraft to aid in rejection of the harmonic disturbances caused by imbalances in the wheels. LMS is a “Plug-in” add on to the feedback loop and is used to reject sinusoidal tones.

PACE current baseline is to use the feedback loop to suppress high frequency jitter, and use the feedforward LMS loop for robustness. PACE control loops are running at high frequency sampling rates, and these pointing algorithms are planned to be implemented on FPGAs. Both the FSM inner loop and FSM/LOWFS outer loops are to be implemented digitally in an FPGA with LOWFS camera running at 1 kHz sampling rate, and strain gauge sensors at 10 kHz. FPGA implementation, also facilitates configuration changes of either loop during flight operations. For example, both compensator coefficients and switches for enabling or disabling the inner loop feedforward or feedback will be configurable with firmware updates from the ground.

MORE ON ROBUST LMS (LEAST MEAN SQUARE)

As described earlier, using feedback alone will cancel the ACS LOS drift, and RWA disturbances up to 10 RPS. However, depending for wheel speeds greater than 10 RPS, RWA disturbances can be large enough to exceed the pointing requirement. For cases where "feedback only" approach does not cancel tonal frequencies of reaction wheels, feedforward control will be used, where the reaction wheel tachometer measurements are used with a special Filtered-x Least Mean Square (Fx-LMS) design that cancels the tonal RWA disturbance while using low bandwidth feedback. The tachometers are used to indicate to the Fx-LMS algorithm where the disturbance frequencies occur. This is a robustness strategy in terms of minimizing the RMS of the true LOS jitter.

Several issues arise when considering how to design the Fx-LMS feedforward control law. [9] The first is that the tachometers used on the HR18-250 Honeywell wheels have low resolution. The (standard) encoders on these wheels have only eighteen sensors per revolution upon which two speed measurements are formed. There is the count-based tachometer (CBT) measurements which counts the number of sensor transitions every 0.25 seconds. There is also the time-based tachometer (TBT) measurements which uses the time to transit the most recent sensor pair to form a speed measurement. These two tachometer measurements have different noise properties with the CBT performing better at high speeds (above 5 Hz) and the TBT performing better at low speeds (below 5 Hz). Before using these two measurements to estimate the wheel speed, they are first averaged using weights based on the measured wheel speed. These averaged wheel speeds together with the wheel torque commands are used in an Extended Kalman Filter to estimate the speed and angle, or phase, of each wheel. Friction is also estimated in this filter. Despite our best efforts, the estimated wheel speed will have errors that must be accounted for by the feedforward control.

One problem with traditional Fx-LMS algorithms is that they are not robust to disturbance frequency uncertainty. By using multiple regressor functions, each at a slightly offset frequency, the width of the notch filter created by the Fx-LMS algorithm can be arbitrarily widened to account for whatever disturbance frequency uncertainty exists. One key detail in the LMS design is to use the wheel phase/angle instead of the frequency/speed estimate in forming the harmonic regressor. This is important since the wheel speed and thus disturbance frequency changes with time due to SRP and other factors.

Fast Steering Mirror (FSM) Assembly

The FSM assembly is composed of the mirror or optic, gimbal mechanism, piezoelectric actuators (PZTs), local sensors (strain gauges), servo electronics, harness, and mechanical mount. WFIRST CGI fast steering mirror mechanism, is shown in Figure 4. CGI FSM is identical to the FSM mechanism that was designed for the Space Interferometry Mission (SIM) at JPL. One of the engineering models of SIM FSM is currently installed on the CGI testbed. CGI FSM has a new electronics design, with control algorithms to be implemented on an FPGA. Currently, JPL is developing FSM electronics that will be tested in the engineering testbed, and eventually will be built for the flight version. The FSM has fully redundant PZT actuators (three sets of paired PZTs separated by 120 degrees), passive momentum compensation, and articulation about the front surface of the mirror cell. As mentioned earlier, strain gauges are affixed to each PZT for the purposes of linearizing the hysteresis inherent in piezoelectric actuators. The linearization is achieved by using a local control loop about each PZT. The PZTs are grouped in pairs (active and redundant elements) and actuate a flexure that amplifies the PZT extension by a factor of two and serves to move both the mirror side and the reaction mass assembly. The first mode of the CGI FSM is 900 Hz but a softer mount is needed to connect the FSM to the optical bench. Although the FSM mechanism is an inherited design, no flight electronics have been designed for this FSM, and low noise PZT amplifiers have been used in the instrument testbeds.

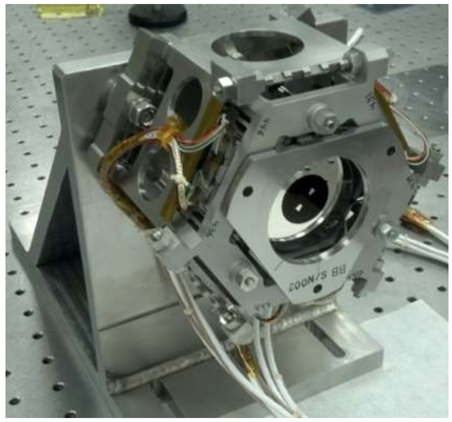

Figure 4: CGI Fast Steering Mirror (FSM)

The FSM will be used for both acquisition and LOS jitter suppression. During acquisition of a new target star the attitude control system is used to place the star in the 9x9 arcsecond on the sky FOV of the science camera with the FSM parked in its home configuration.

The CGI Direct Imager (DI) centroid measurements of the star location will be fed to the ACS for bias offload. This bias offload will result in placing the star from the CGI DI sensor into the LOWFS capture range. From this point, the FSM is used to move the LOS from the edge of the LOWFS FOV to the center of the LOWFS FOV. Currently, the CGI FSM stroke range is +/-0.3 arcsecond. This is only a fraction of the nominal +/-71.45 arcsecond SIM FSM stroke. Having smaller stroke allows one to have higher resolution FSM with lower quantization error. No additional stroke is required from either the FSM or the mount for alignment during integration with the optical bench since all other optics will be aligned relative to the FSM. Shims will be used if necessary to make alignment adjustments during integration.

As the LOS varies, the FSM will develop an offset. This offset will be sensed by strain gauges, the local sensors on the FSM and mapped to an attitude correction to send to the spacecraft ACS. This attitude correction desaturates the FSM stroke and will be used by the ACS system to improve pointing knowledge and accuracy. Maintaining the FSM near its center is important in terms of mitigating beamwalk, which can adversely impact CGI contrast performance.

SIMULATION RESULTS

PACE has developed a time-domain Control Analysis Simulation Testbed (CAST) that has high fidelity models of dynamics, sensors, and actuators. This simulation includes all the control loops that are employed in the pointing architecture, as well as disturbance sources models, such as reaction wheels disturbances.

CAST can be used for LOS pointing performance evaluation for the entire CGI science observations. The output is the LOS error at the occulter mask of the CGI. The following results are from a set of CAST runs for different cases. In these simulations, we compare the performance of the control architecture using three sets of feedback loops with bandwidths of 2 Hz, 10 Hz, and 20 Hz, and by either turning feedforward LMS on or leaving it off. In each case there are 10 runs, where the six reaction wheel speeds are randomly selected between +/-10 RPS. Table 1 tabulates some of different cases that have been evaluated using CAST.

Table 1: CAST runs with feedback, and feedforward LMS

Case #	Feedback Bandwidth (Hz)	LMS	RW Speed (RPS)	Lowpass torque cmd And calibrated tach
1	2	Off	1-10	Off
2	2	On	1-10	Off
3	2	On	1-10	On
4	20	Off	1-10	Off
5	20	On	1-10	Off
6	20	On	1-10	On
7	10	Off	1-10	Off
8	10	On	1-10	Off
9	10	On	1-10	On

Figure 5 shows a summary of results for cases in Table 1. For low bandwidth feedback loops, at 2, and 10 Hz, requirements are not met with just feedback, (cases 1, 7) and requires LMS to be turned On, to meet requirements (cases 2, 8). In these cases, feedback loop bandwidth is not high enough to reject the jitter at wheel speeds up to 10 RPS. However, when the feedback loop bandwidth is at 20 Hz, (case 4), requirements are met with feedback only case, while LMS provides an improvement in robustness and margin (case 5). For cases when LMS is on, there are slight improvements when torque commands are filtered and tachometer measurements are calibrated, but this is not necessary to meet performance requirements (cases 3, 6, 9). The current baseline is to have a feedback loop with 20-30 Hz bandwidth, and optional LMS, in case there is need to reject tonal disturbances.

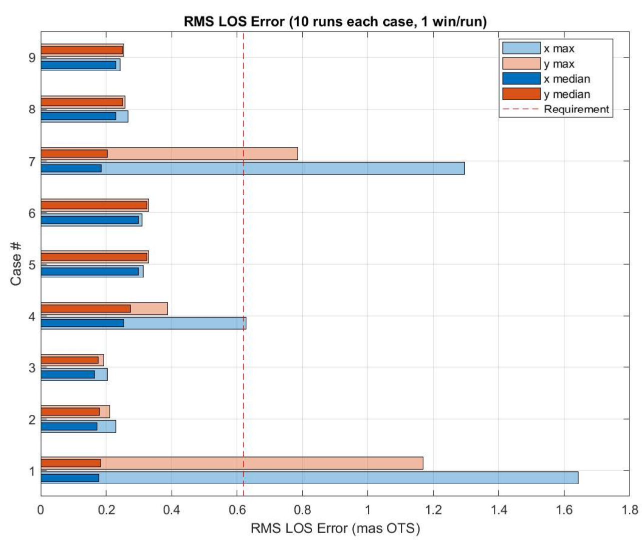

Figure 5: Summary of results for cases in Table 1

CONCLUSION

In this paper we explained WFIRST CGI pointing architecture, and mitigation strategies to reject high frequency Line of Sight jitter. The pointing system includes three nested feedback loops: ACS, FSM local control, and FSM/LOCAM feedback loop, to remove low frequency drift, and suppress high frequency jitter induced by spacecraft reaction wheel disturbances. The feed-forward loop (LMS) rejects high frequency tones excited by reaction wheels tonal frequency. We also show some preliminary results with reaction wheels speeds constrained to +/-10 RPS. These results show that CGI meets tight pointing requirements with feedback loop bandwidth at 20 Hz, while feedforward LMS adds robustness and margin. However, for feedback loops with lower bandwidths, a feedforward LMS is required to meet pointing requirements. Higher fidelity models with all updated observatory models, that includes a flexible CGI bench model will be available in Spring 2019, and pointing assessments for these models will be available in Summer 2019 at the CGI PDR.

ACKNOWLEDGMENTS

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